DE LA RECHERCHE À L'INDUSTRIE

HIGH-ENERGY DATA FOR ADS (AND OTHER APPLICATIONS)

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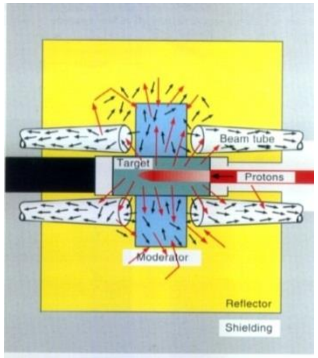
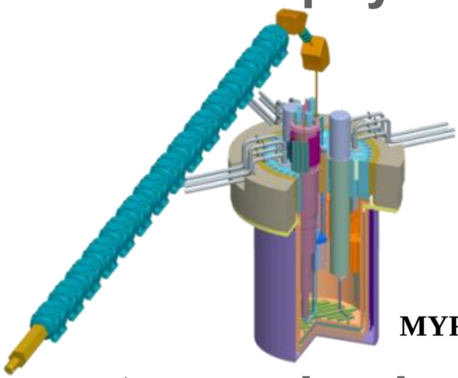
IMPORTANCE OF HIGH-ENERGY DATA

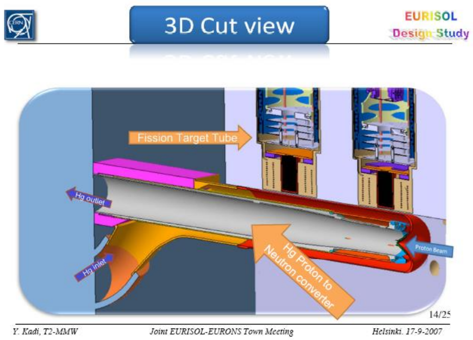
- Neutron sources for material science, condensed matter physics (SNS, JPARC, ESS…)



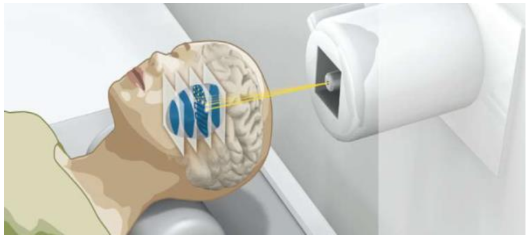


MYRRHA

- Accelerator-driven sub-critical reactors for nuclear waste transmutation (MYRRHA…)



- Production of radioactive beams for fundamental nuclear physics studies (ISOLDE CERN, FRIB, EURISOL…)



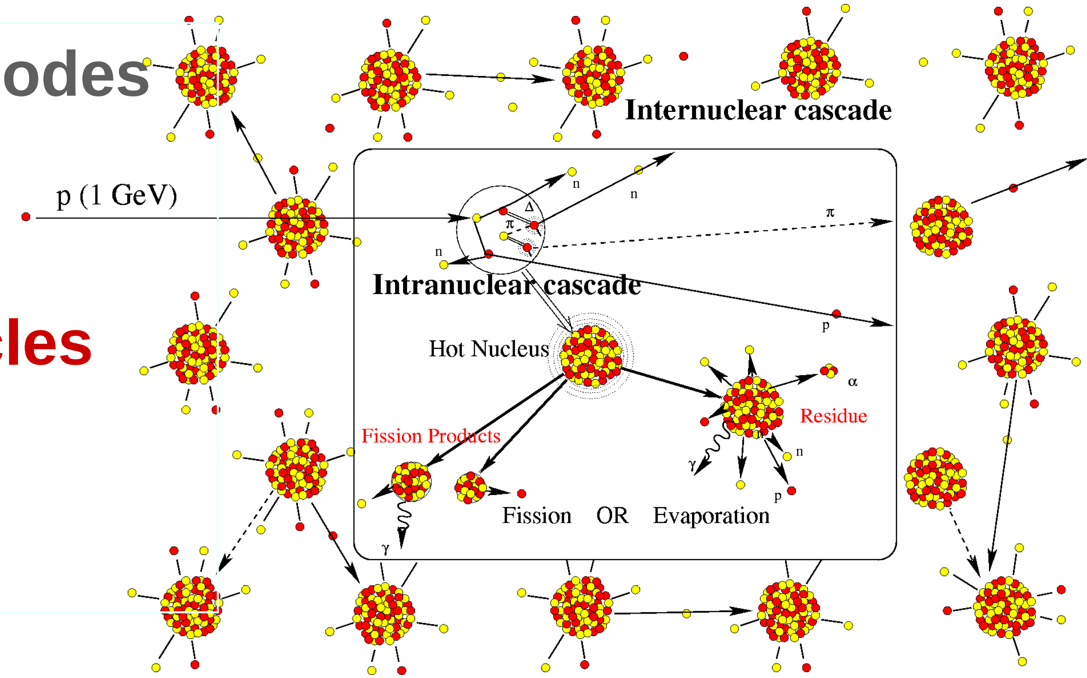
- Therapy with protons or heavy ions beams

- Radiation protection, damage to electronic circuits in space or near accelerators

SIMULATION CODES

- Monte-Carlo transport codes (MCNPX, MARS, PHITS, FLUKA, GEANT4…)

  propagation of all particles created in elementary interactions



➢Above 150-200 MeV : nuclear physics models i.e. Intra-Nuclear Cascade (+ Pre-eq) + evaporation-fission ➔ cross-sections, properties of emitted particles directly used by the transport codes

➢Below 150-200 (20) MeV : evaluated data libraries but not all isotopes up to 200 MeV, loss of correlations

HIGH-ENERGY DATA FOR SPALLATION DEVICES

Neutron production

- number ➔ **power of the system / needed accelerator intensity**
- energy, spatial distribution (DDXS)➔ **target optimisation, damage in window and structures**
- high energy neutrons ➔ **shielding**

Charged particle production

- gas (H_2, He) production ➔ **embrittlement, swelling**
- energy ➔ **DPA, energy deposition**

Residual nuclide production

- element distribution ➔ **corrosion, change in metallurgical properties**
- isotope distribution ➔ **activity (short lived isotopes), radiotoxicity (long lived isotopes), decay heat, delayed neutrons**
- recoil energies ➔ **DPA in window and structures, energy deposition**

HIGH-ENERGY DATA FOR SPALLATION DEVICES

Thin target data

- Goal: better understanding of reaction mechanisms ➔ improvement of physics models
- Need of data covering the full range of target masses and incident energies ➔ contrary to low energies rough sampling sufficient
- No real adjustable parameters in the models ➔ reliable interpolation and extrapolation
- No real adjustable parameters in the models ➔ difficulty to improve on one side without degrading elsewhere

Thick target data

- Model and code system validation
- Direct measurement of some quantities of interest in realistic conditions

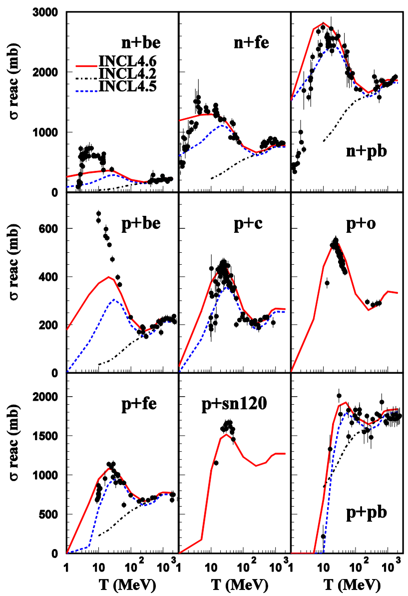
EU COORDINATED EFFORT ON HIGH-ENERGY DATA

- **Motivation: ADS for nuclear waste transmutation**
  - FP5: HINDAS
  - FP6: EUROTRANS/NUDATRA
  - FP7: ANDES

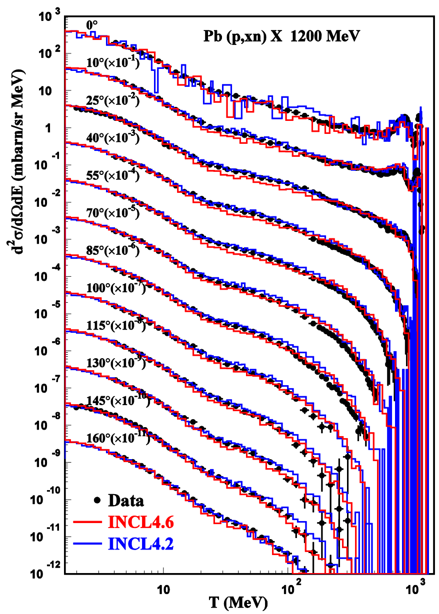
- **Large amount of (mostly p-induced) high-quality data collected**
  - p-induced neutron DDXS at Saturne, n-induced at Uppsala and UCL
  - Isotopic distribution of residues in reverse kinematics at GSI
  - Neutron multiplicity distributions, LCP DDXS by NESSI
  - LCP, IMF DDXS by the PISA collaboration
  - Residue excitation functions by Michel et al., Titarenko et al.
- **Improvement of nuclear models**
  - INCL4/ABLA tested against the available data (Liège-Saclay-GSI)
  - implementation into high-energy transport codes (MCNPX, PHITS, GEANT4)

VALIDATION OF INCL4 AGAINST EXPERIMENTAL DATA

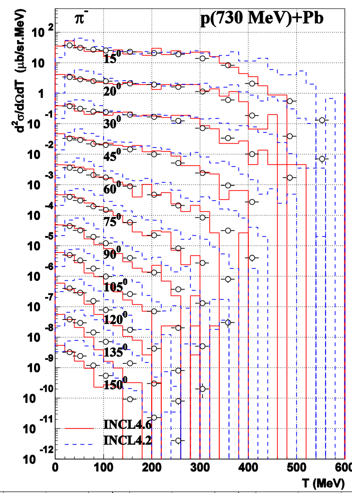
Reaction Cross-section



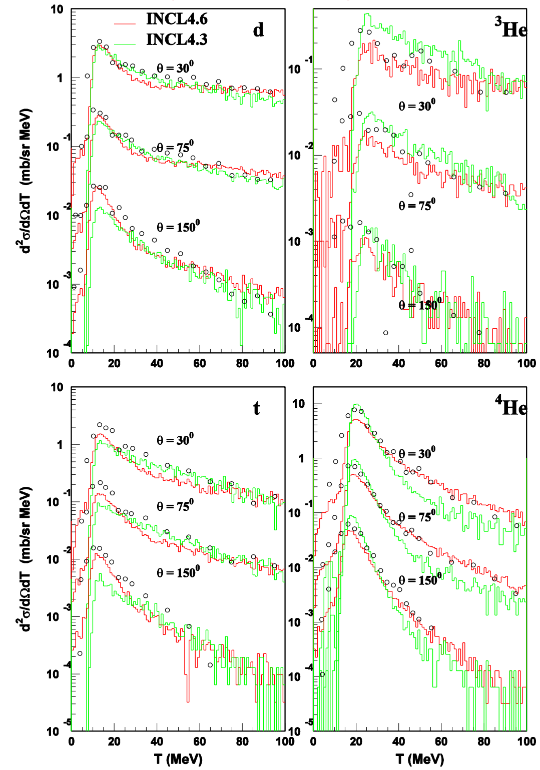
Neutron production



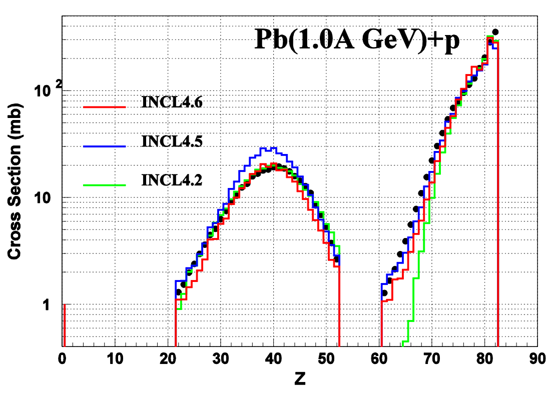
pion production

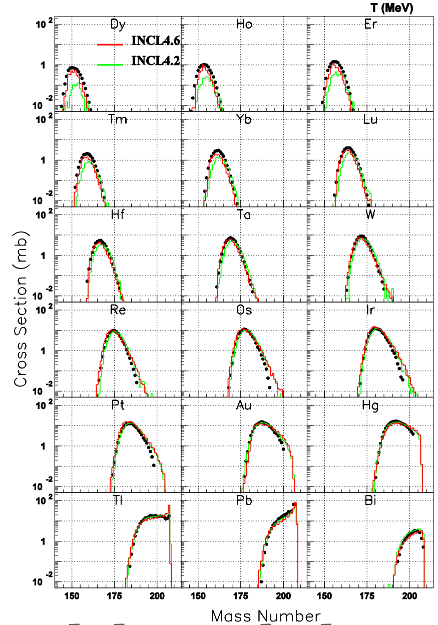


LCP production p(1200 MeV) + Ta



Residue mass distribution





Isotopic Cross-section

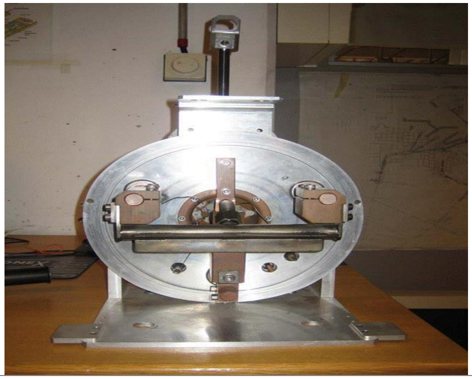
A. Boudard et al., PRC 87, 014606 (2013)

INCL4.6 Intra-Nuclear Cascade model coupled to ABLA07 de-excitation

PRODUCTION OF At IN THE LBE ISOLDE TARGET

Measurement of At isotopes released from a liquid lead-bismuth (LBE) target irradiated by a proton beam of 1.4 and 1 GeV by the ISOLDE IS419 experiment (Y. Tall et al., ND2007)

♦ **not reproduced by any calculation**



Two production channels:

➢ **Double charge exchange (p,π⁻) induced by primary protons**

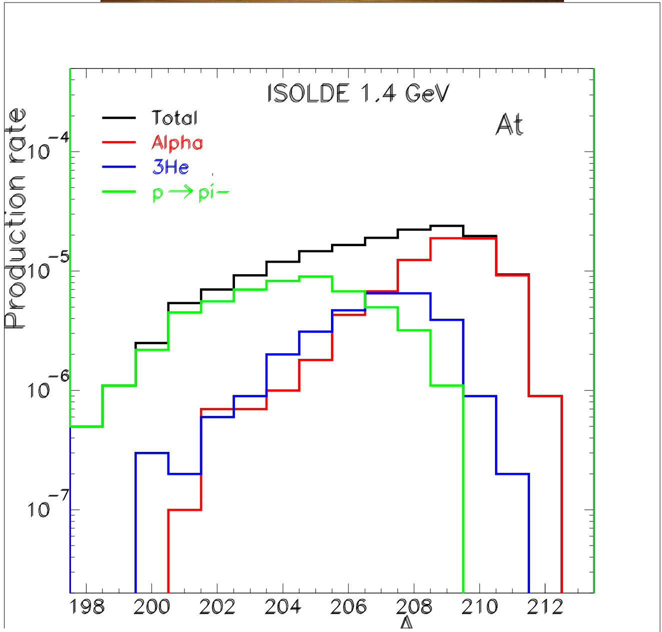
$$p + {}_{83}Bi \rightarrow {}_{85}At + xn + \pi^-$$

➥ **dominant for light isotopes (A ≤ 206)**

➢ **Secondary reactions induced by helium nuclei**

$${}_{2}\mathrm{He} + {}_{83}Bi \rightarrow {}_{85}At + xn$$

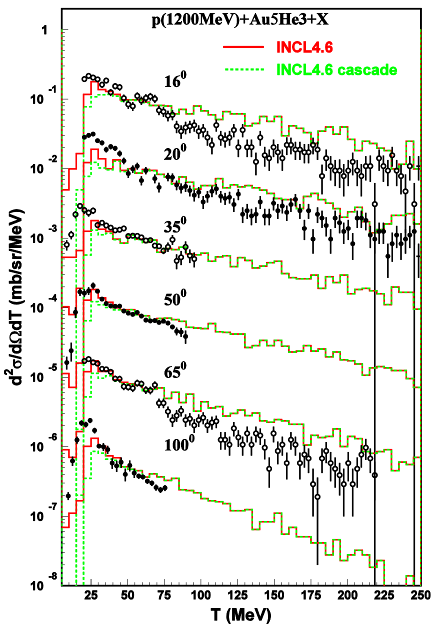
➥ **dominant for heavy isotopes**



Calculations with INCL4.6-ABLA07 in MCNPX2.7.b

SECONDARY HELIUM-INDUCED REACTIONS

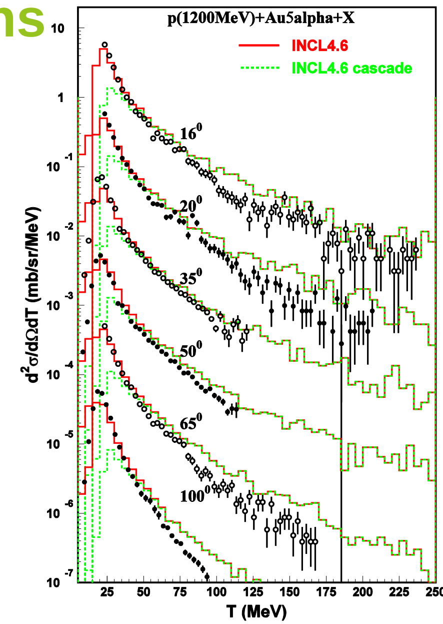
Helium production in primary reactions



^{3}He

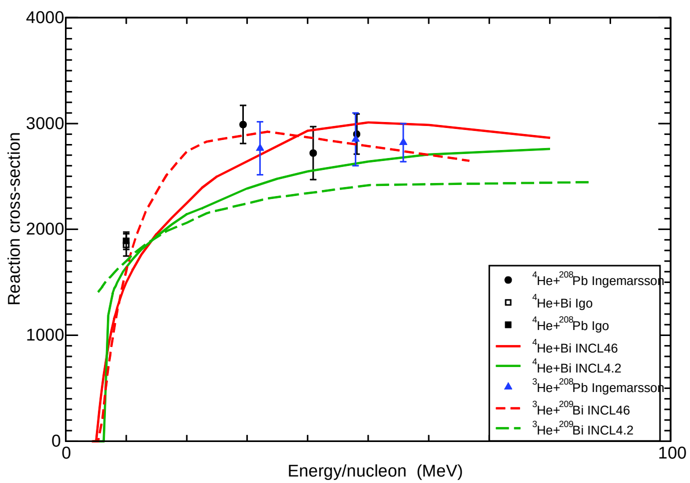
p(1200 MeV) + Ta
(Herbach et al.)

^{4}He

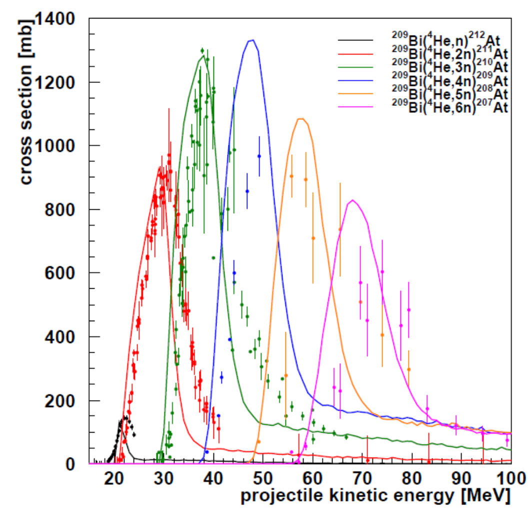


Calculation: INCL4.6 coupled to ABLA07

He-Bi total reaction XS



Excitation functions (^{4}He,xn)



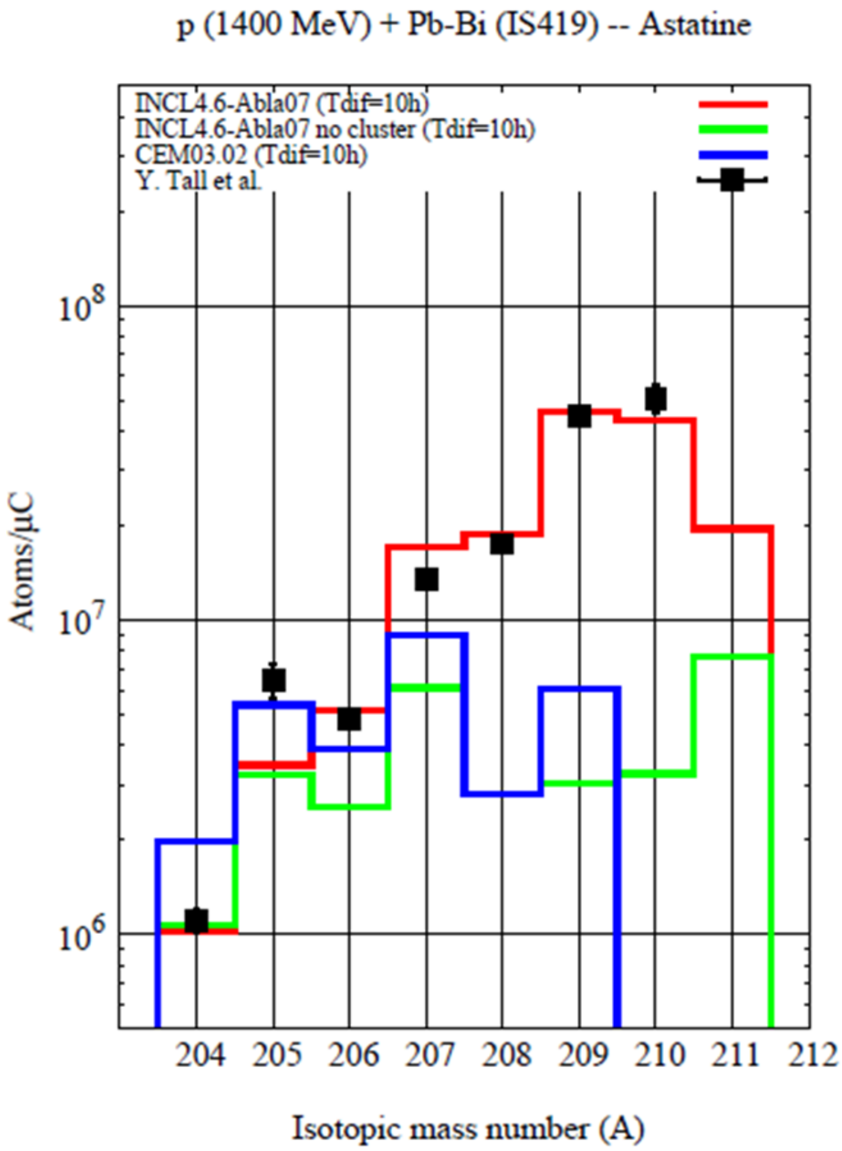
PRODUCTION OF At IN ISOLDE LBE TARGET

J.C. David et al., EPJA 49, 29 (2013)

Data from Y. Tall et al., ND2007

Calculations: INCL4.6-ABLA07 in MCNPX2.7.b

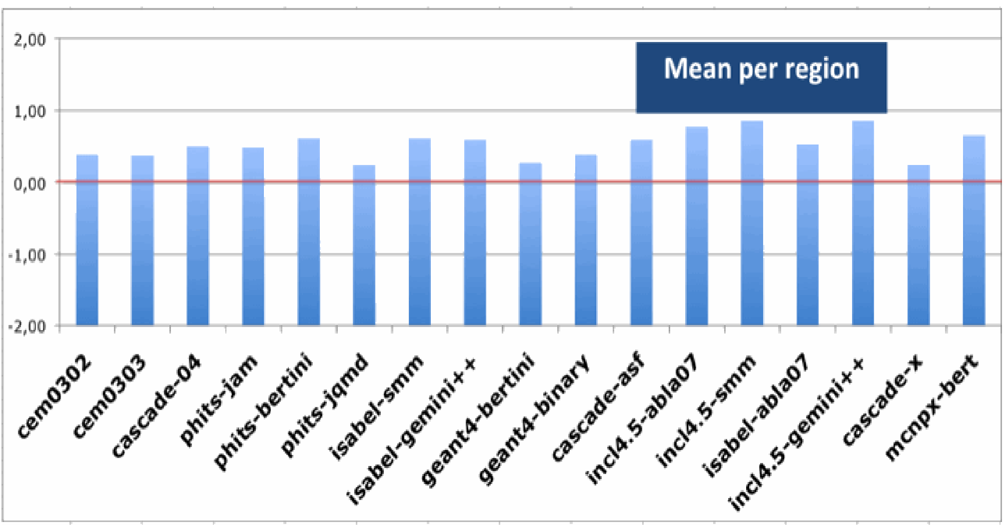
↪ Importance of helium produced by coalescence



IAEA benchmark of spallation models

Neutron double differential cross-sections global analysis:

Division of the spectra in 4 energy regions: evaporation, pre-equilibrium, pure cascade and quasi-elastic

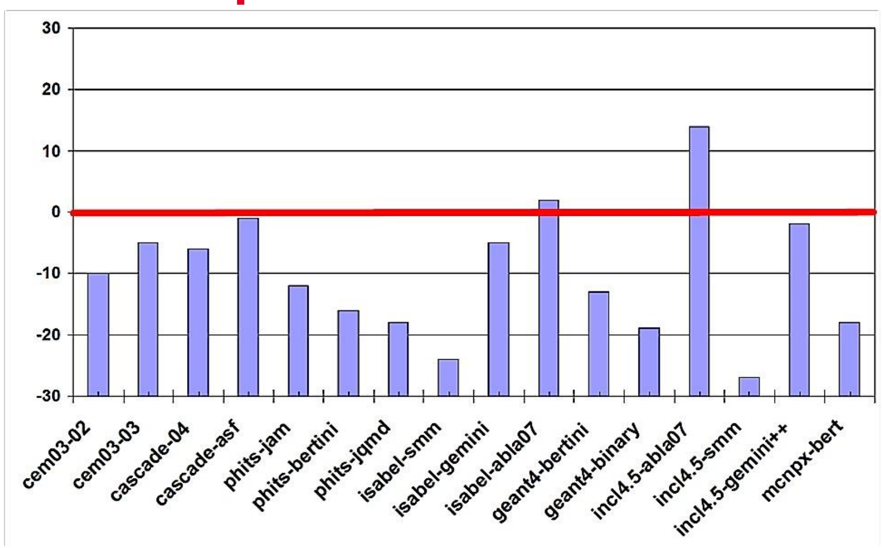


http://www-nds.iaea.org/spallations

Residue global analysis:

Division of the distributions in mass/charge regions: evaporation residues, deep spallation, fission and intermediate mass fragments

Isotopic distributions



Quality	Points
Good	2
Moderately good, minor problems	1
Moderately bad, particular problems	-1
Unacceptably bad, systematically wrong	-2

Conclusions from the IAEA benchmark

- Situation largely improved compared to previous benchmarks
  - More experimental data to compare with
  - Global quality of models improved
- Most models well predict neutron and proton DDXS
  - Predictions of neutron production and spectra rather reliable
- Not all models reproduce the high energy tail of composite LCP : necessity of a specific process (coalescence or pre-equilibrium)
  - Importance of having such a mechanism for tritium and ^{3}He prediction
- Heavy evaporation residues well predicted but large discrepancies between models for a lot of nuclides
- Residues very sensitive to the de-excitation stage, necessity to describe all reactions channels correctly (fission, IMF production…)
  - Large difference from one isotope to another: necessity to check prediction of both isotopic distributions and excitation functions

ARE THERE STILL MISSING DATA?

NEW EU PROJET: CHANDA

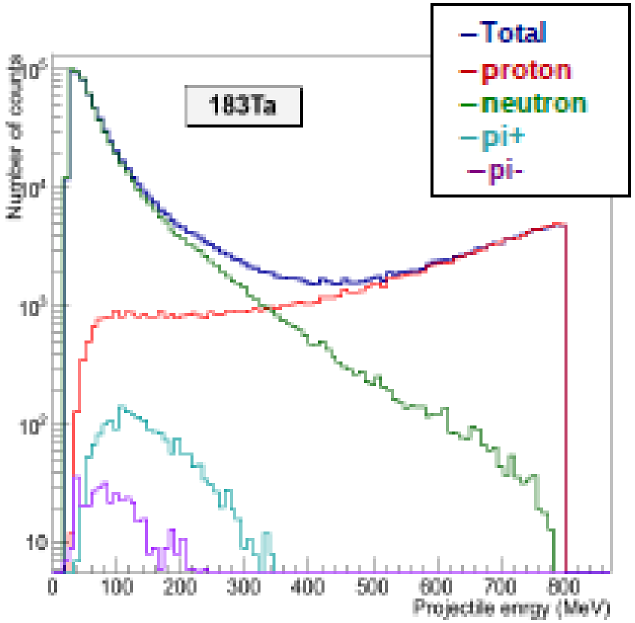
Workpackage on high-energy data

- Development of a methodology, specific of high-energy reactions, for uncertainty assessment of safety parameters in ADS, with a particular focus on MYRRHA
- Minimizing the present uncertainties by
  - addressing known gaps in the models,
  - providing more constraining data for models: coincidence between residues and particles
  - integral benchmarking

Neutron-induced reactions

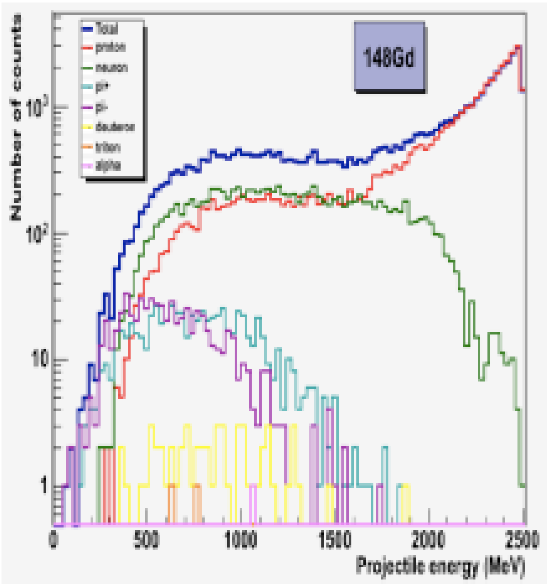
- Most of the data collected during the last 20 years concerned p-induced reaction data
- Secondary reactions of high energy neutrons play an important role in the production of residues, in particular the highest mass ones
- Comparison of n/p induced reactions interesting for models

800 MeV p on a thick W target



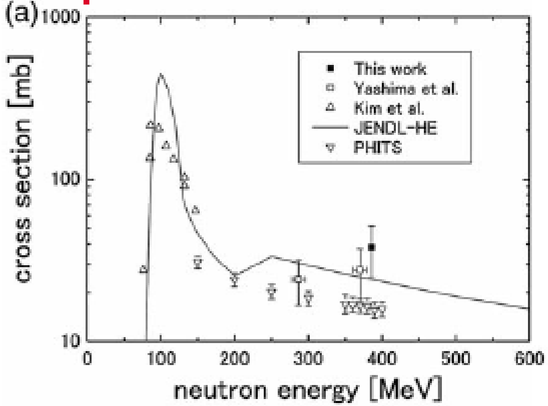
From A. Leprince et al., ICRS12

^{148}Gd produced in the ESS target



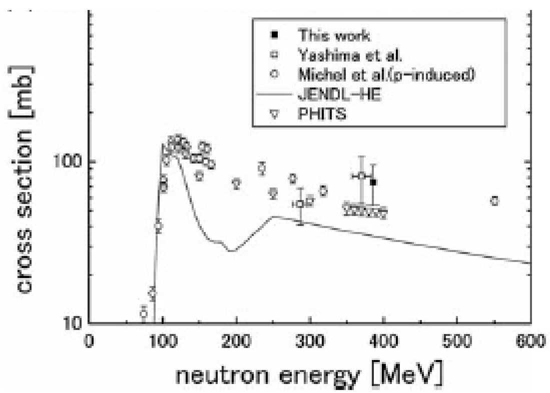
- very few available data
- some attempts to extract n-induced excitation functions from thick target experiments (meteorites)

^{201}Bi produced in n+Bi reaction

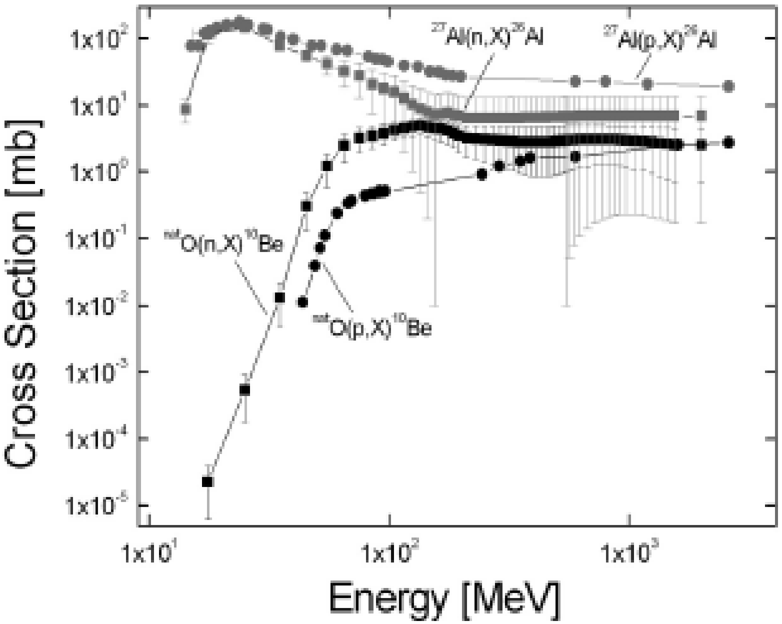


Measurement at RCNP Osaka at 386 MeV by Tashima et al. (2013)

^{200}Pb produced in n+Bi reaction



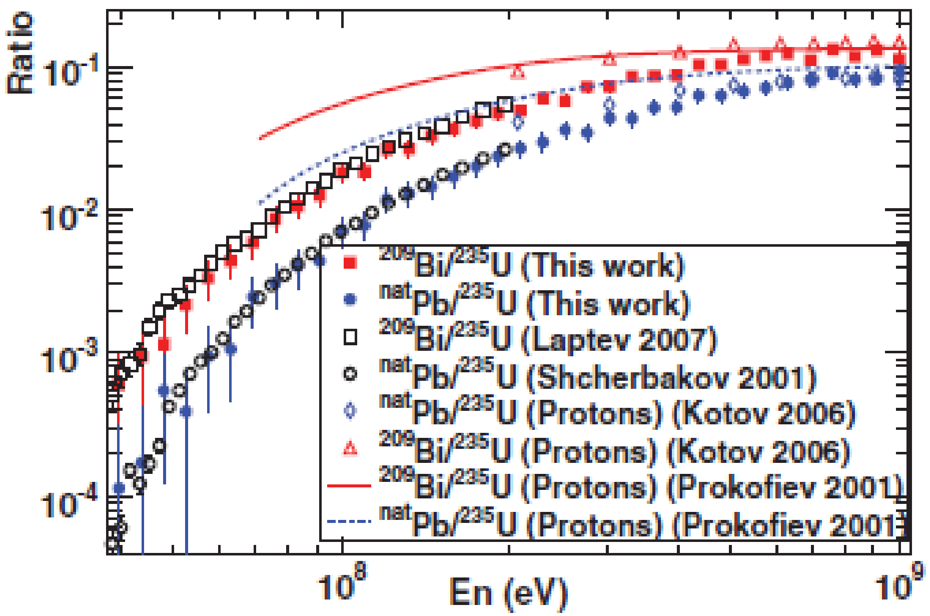
Production of ^{10}Be from O and ^{26}Al from Al



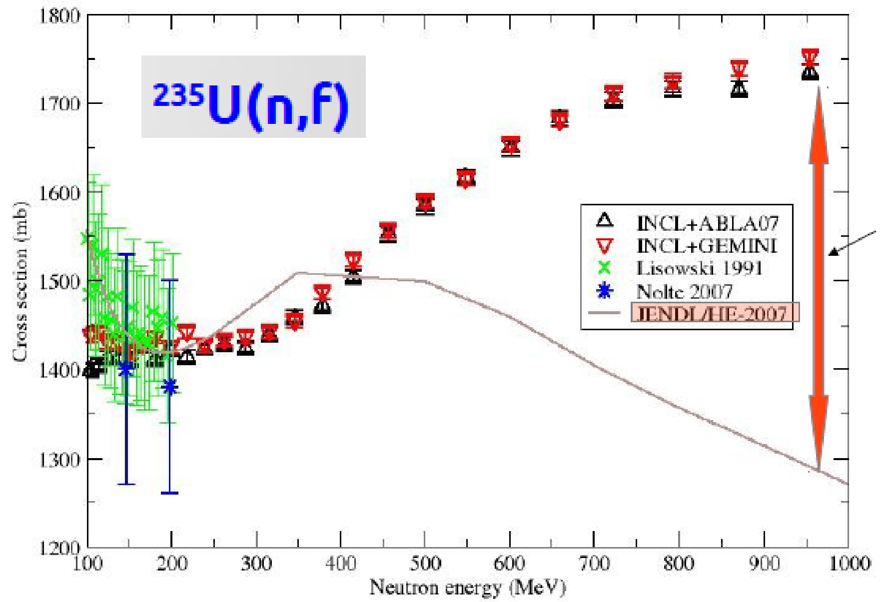
From Leya and Masarik (2009)

n-INDUCED FISSION CROSS SECTION MEASUREMENTS

- only measurements with respect to ^{235}U
- no data above 200 MeV: use of JENDL-HE
- **need for absolute cross-sections measurements**

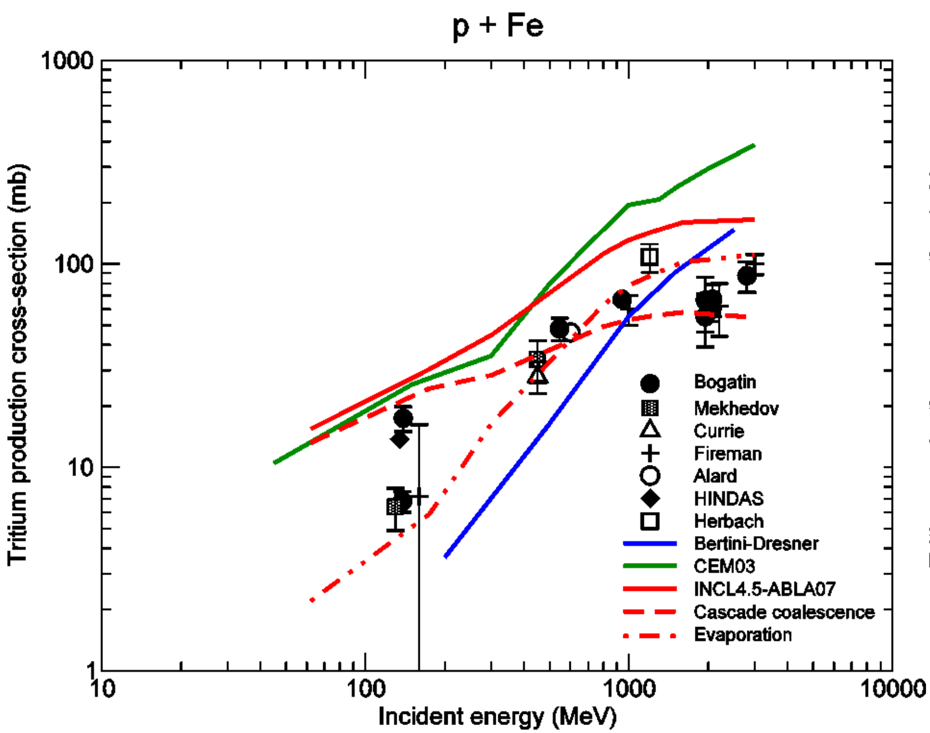


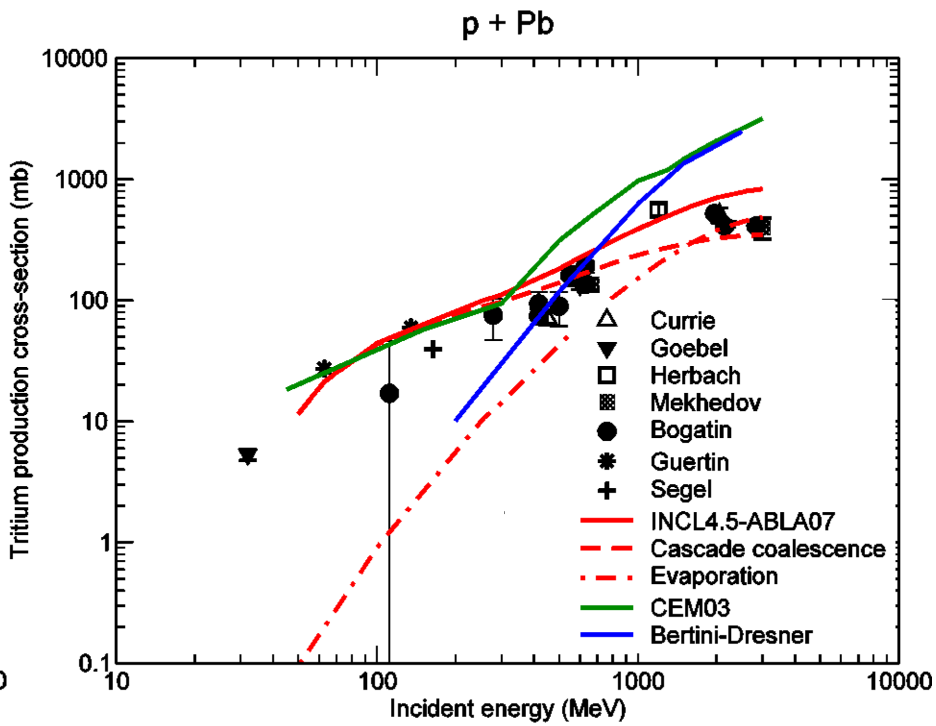
N_TOF measurement :
^{209}Bi and ^{nat}Pb
Tarrio et al., PRC 83 (2011)



Calculation with INCL4 which gives good results for p-induced fission cross-sections
From S. Lo Meo and D. Mancusi

TRITIUM PRODUCTION





NIM B 268 (2010) 581

➢Cluster emission during the INC stage very important for t

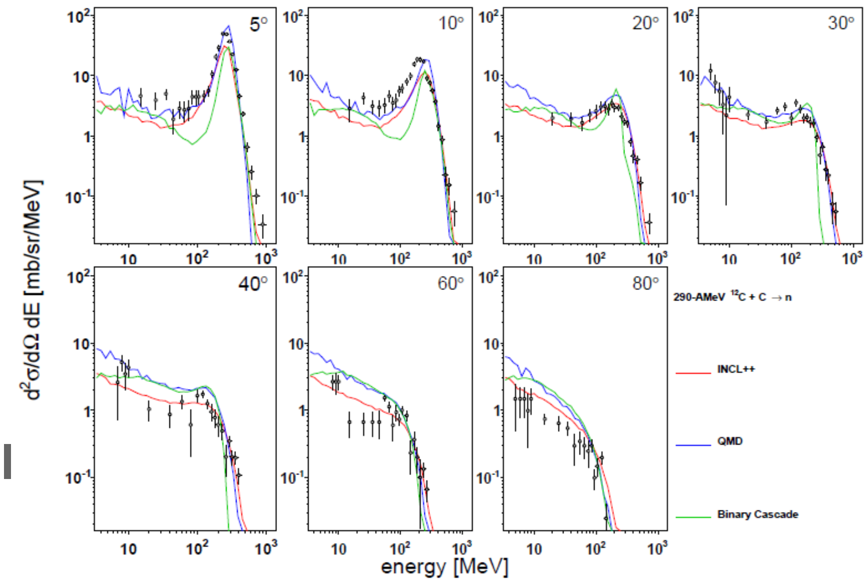
➢ **INCL4.5-ABLA07 gives a very good agreement with data all over the energy range, generally better than other models in MCNPX**

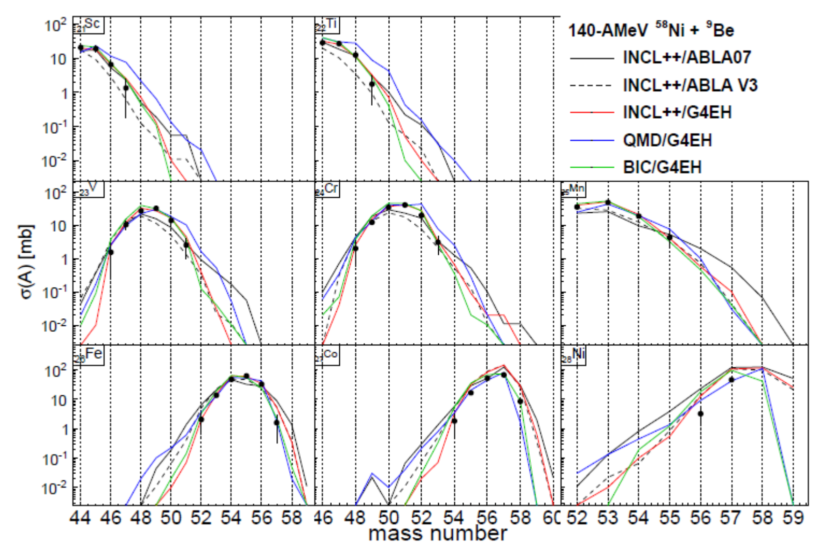
INCL++ EXTENSION TO LIGHT-ION INDUCED REACTIONS

- **Motivations**
  - Hadrontheray
  - Space radiation protection
  - Simulations of nuclear physics experiments
- **Model development:**
  - New C++ version of the INCL4.6 model (A. Boudard et al., PRC 87, 014606 (2013)) extended to light-ion induced reactions
- **Implementation into GEANT4:**
  - Release 9.6: INCL++ with LI extension up to ^{18}O coupled to G4-deexcitation
  - New physics lists: QGSP_INCLXX (+ QGSP_INCLXX_HP, FTFP_INCLXX, FTFP_INCLXX_HP to appear with next β-release)

D. Mancusi et al., submitted to PRC

$^{12}C + ^{12}C$ 290 MeV/u



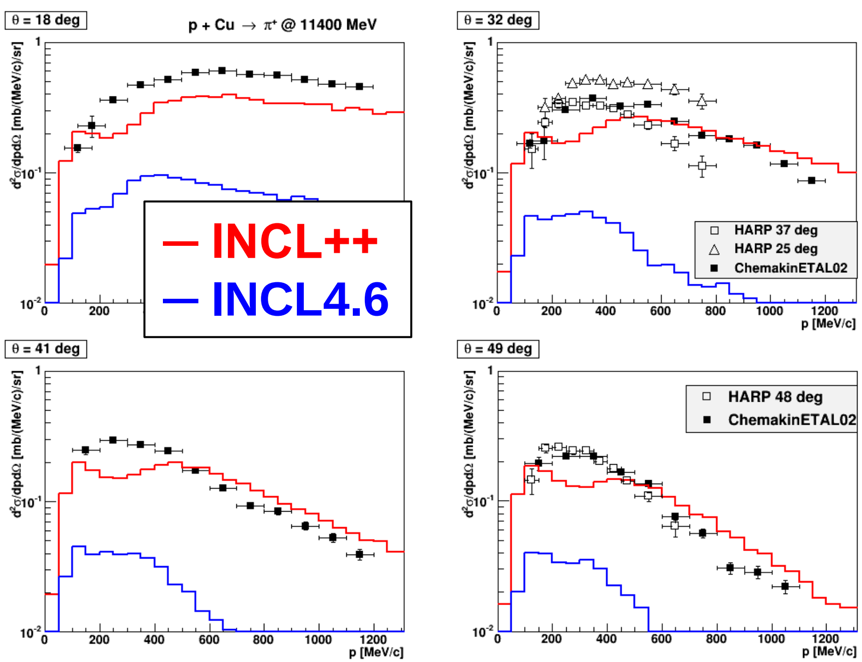


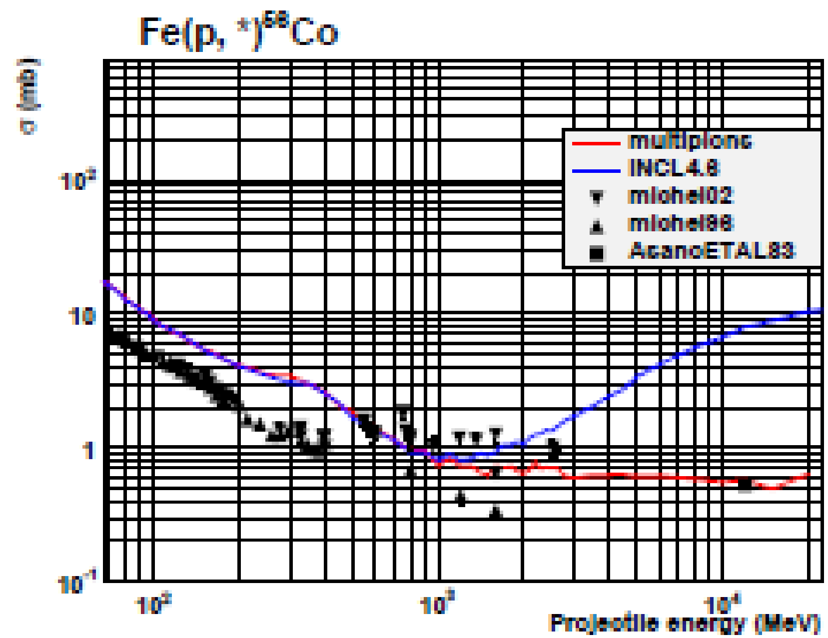
HIGH-ENERGY EXTENSION

- **Motivations**
  - Experiment simulations, radiation protection
  - Muon production
- **Multi-pion channels already implemented** (Pedoux et al., Adv. in Space Res. 44 (2009))

p+Cu 11.4 GeV

Data from HARP coll. and Chemakin PRC65





From T. Goigoux, Master thesis

DATA NEEDS FOR EXTENSION OF THE MODEL

- For both light-ion and high-energy extensions
  - need of a comprehensive validation on a broad set of data as was done for the nucleon-induced reaction between 100 MeV and 2-3 GeV
  - there are available data but not covering all produced particles and nuclei
  - a lot of data cannot be used because of not clear acceptance or trigger conditions: simple inclusive DDXS would be useful
- in the case of high-energy extension
  - need for further DDXS for the production of pions and strange particles

ARE THERE STILL MISSING DATA?

- **Neutron-induced reactions between 100 and 500 MeV**
  - **All types but mostly residue production**
- **Tritium production**
  - **Mainly total production but also DDXS**
- **Residue production for some isotopes of interest**
  - **excitation functions and production in representative thick targets**
- **Coincidence experiments to better constrain the models**
- **Ion-induced reactions**
  - **Inclusive DDXS**
  - **residue production**
- **Higher energies up to 10-15 GeV**
  - **Inclusive DDXS production of in particular pions and kaons**
  - **Residue production**
  - **In both p and ion- induced reactions**